# Stratospheric ozone causes a negative feedback in $CO_2$-driven climate change simulations

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## Radiative forcing, radiative feedback and climate sensitivity

The climate sensitivity $\lambda$ describes the global mean surface temperature response ($\Delta T_S$) to a radiative forcing $RF$:

$$\Delta T_S = \lambda \cdot RF$$

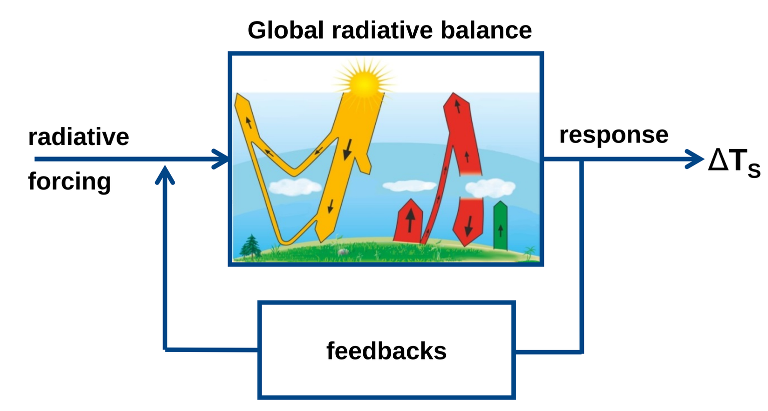
$\lambda$ is a model dependent parameter, with currently insufficient constraining from observations, as the climate sensitivity of the real climate system is largely unknown.

$\lambda$ crucially depends on the strengths of a number of radiative feedbacks ($\alpha_x$):

$$-\frac{1}{\lambda} = \alpha = \Sigma \alpha_x$$

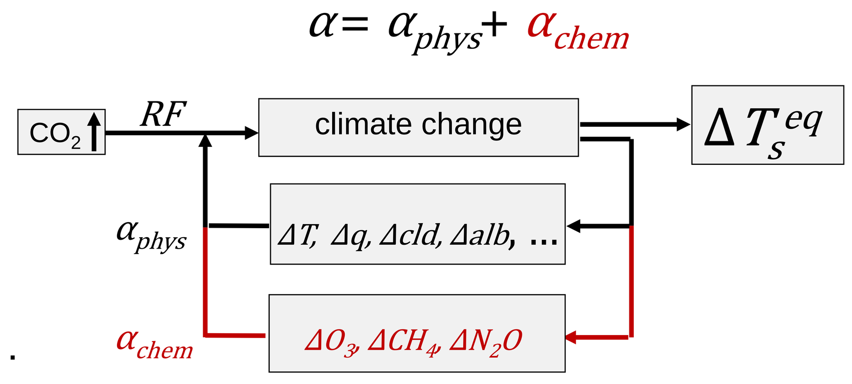
Classical atmosphere ocean models include feedbacks induced by physical climate variables like temperature (via Planck, lapse rate and stratospheric temperature feedbacks), water vapour, clouds, snow and ice:

$$\alpha_{phys} = \alpha_{pla} + \alpha_{LR} + \alpha_{str} + \alpha_q + \alpha_{cld} + \ldots$$

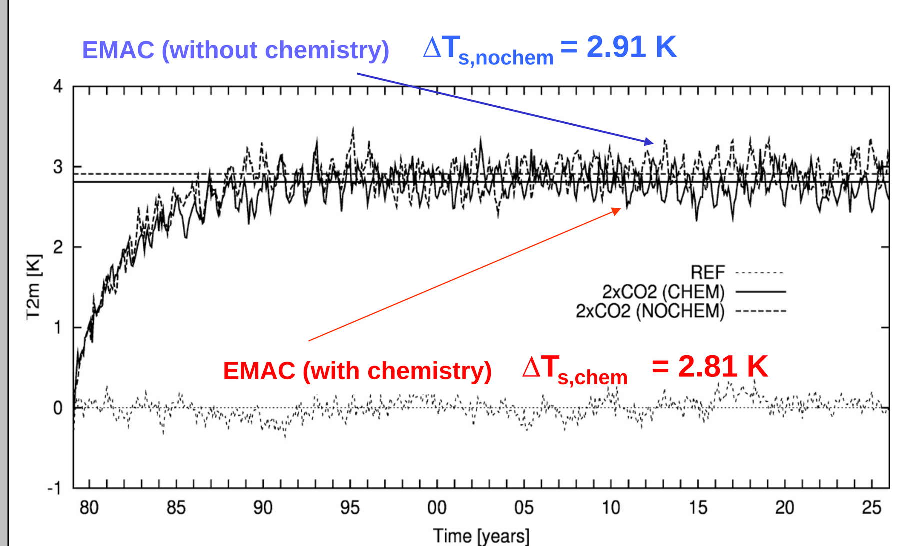



The potential importance of chemical feedbacks has only been explored quite recently, as interactively coupled chemistry-climate models have become available for multi-decadal equilibrium climate change simulations.

$$\alpha = \alpha_{phys} + \alpha_{chem}$$




## Climate sensitivity with and without chemistry interactions




Equilibrium climate change simulations forced by a $CO_2$ increase have been conducted with the **EMAC** (ECHAM/MESSy) climate model, with and without interactive chemistry.
They reveal a moderate but significant reduction of the climate sensitivity to $CO_2$, if chemical feedbacks are included. The reduction is found to be **3.4%** in case of a $CO_2$ doubling (while increasing to **8.4%** in case of a $CO_2$ quadrupling).
Successful feedback analysis depends on the $CO_2$ forcing to exceed a certain threshold in order to limit statistically uncertainty .

| Simulation | | Radiative forcing $Wm^{-2}$ | Interactive chemistry | Climate sensitivity $\lambda$ K/$Wm^{-2}$ | [95% confi.] |
|---|---|---|---|---|---|
| Increase of $CO_2$ by 75 ppmv | +75CO2 | 1.06 | no<br>**Yes** | 0.73<br>**0.63** | [0.67; 0.79]<br>**[0.57; 0.68]** |
| Doubling of $CO_2$ | 2xCO2 | 4.13 | no<br>**yes** | 0.70<br>**0.68** | [0.69; 0.72]<br>**[0.66; 0.69]** |
| Quadrupling of $CO_2$ | 4xCO2 | 8.93 | no<br>**yes** | 0.91<br>**0.84** | [0.90; 0.92]<br>**[0.83; 0.85]** |

**Robustness:** Other comparable studies also find a reduction in climate sensitivity with chemistry included: Muthers et al. (2014) report a **7%** reduction for 4xCO2 from their SOCOL/MPIOM model, while in Nowack et al. (2015) even a **20%** reduction for 4xCO2 is reported from simulations with HADGEM3 AO.

## Global mean feedbacks

| | 2xCO2 | 4xCO2 |
|---|---|---|
| $\alpha_{O3}$ | **–0.022** | **–0.015** |
| $\alpha_{O3}^{trop}$ | **+0.008** | **+0.009** |
| $\alpha_{O3}^{strat}$ | **–0.031** | **–0.024** |
| $\alpha_{CH4}$ | **<0.002** | **<0.002** |
| $\alpha_{N2O}$ | **<0.002** | **<0.002** |
| $\Delta\alpha_q$ | **–0.027** | **–0.047** |
| $\Delta\alpha_q^{trop}$ | **+0.008*** | **–0.010*** |
| $\Delta\alpha_q^{strat}$ | **–0.034** | **–0.042** |
| | [$Wm^{-2}K^{-1}$] | [$Wm^{-2}K^{-1}$] |

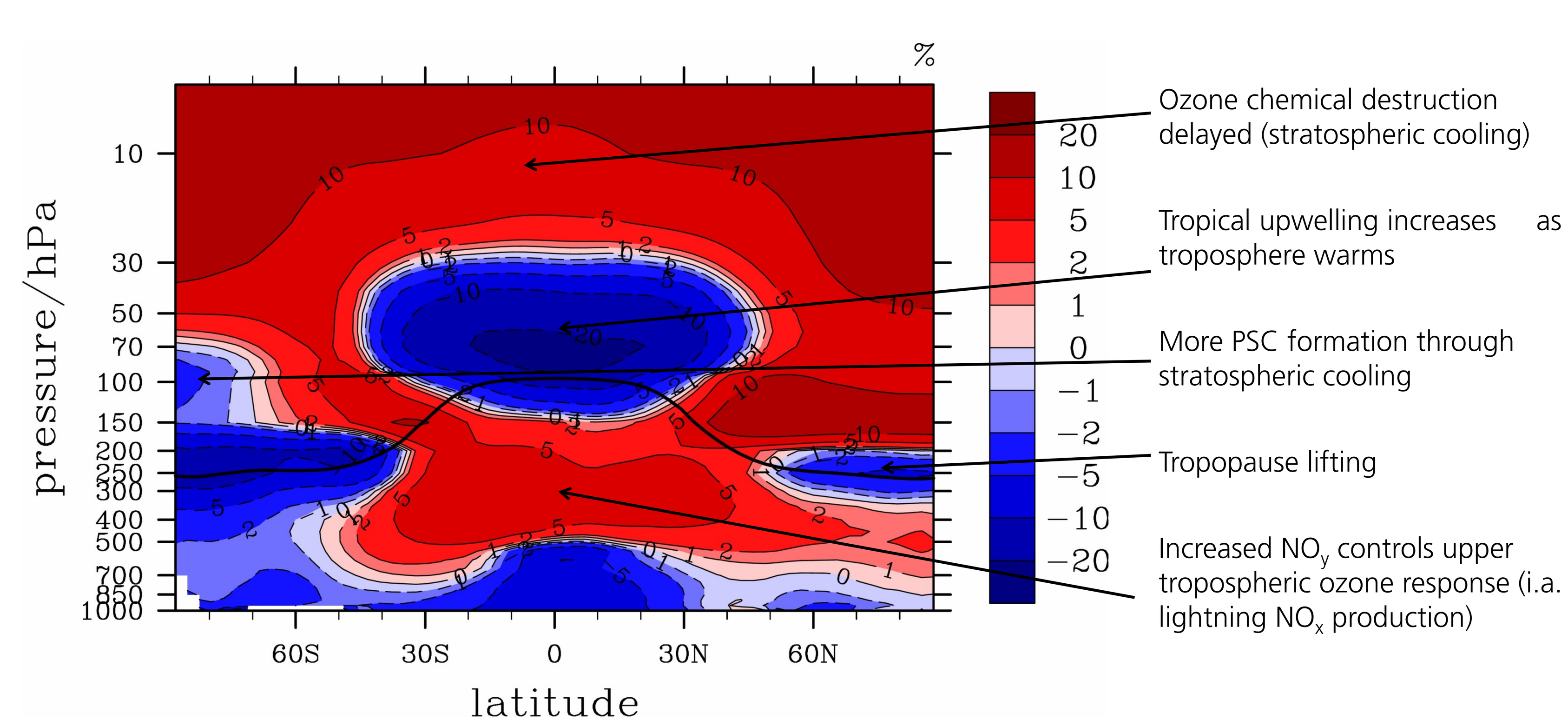
**Limited by model setup** ($\alpha_{CH4}$, $\alpha_{N2O}$)

* statistically not significant

The main „chemical" feedback is induced by ozone ($\alpha_{O3}$). It is negative. Other feedbacks are insignificant ($\alpha_{CH4}$, $\alpha_{N2O}$), possibly due to conceptual limitations of the model setup.

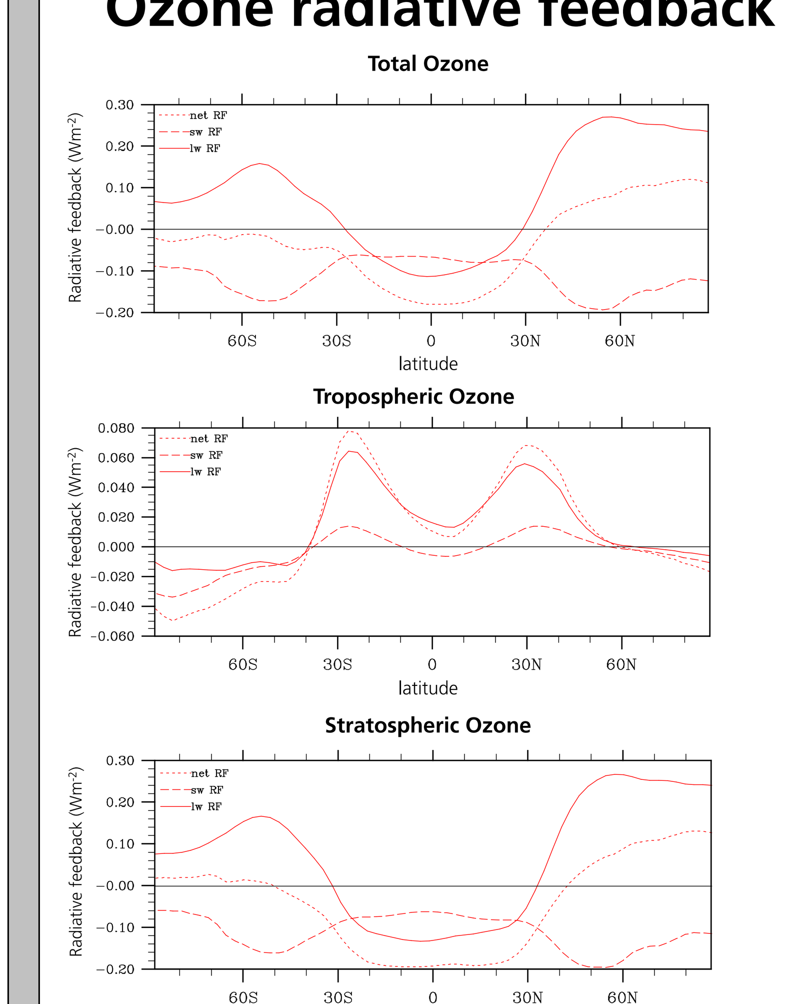
Some physical feedbacks, notably that from stratospheric water vapour ($\alpha_q^{strat}$), can get significantly modified in the presence of an ozone feedback (see box below). Hence, they contribute to the changing climate sensitivity in the $CO_2$ increase simulations including interactive chemistry, too.

## $O_3$ concentration change pattern from $CO_2$ induced warming



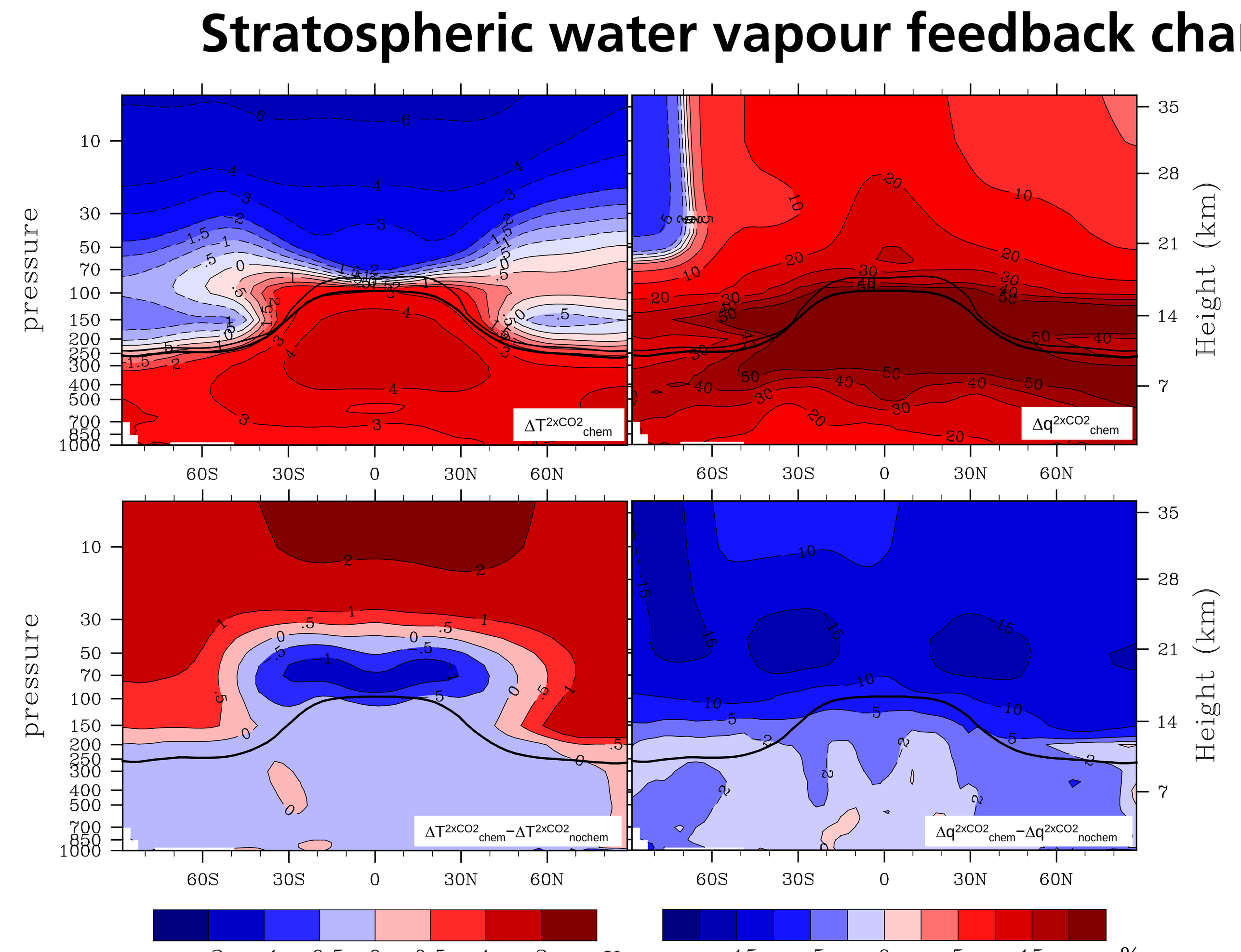

$CO_2$ doubling and its corresponding climate response induce a characteristic, yet complex, change pattern of atmospheric ozone. Additional diagnostic techniques help to unravel the individual effects contributing to the overall change pattern.
Ozone changes of varying sign in various altitude and latitude regimes in turn lead to considerable spatial variability with respect to the associated radiative feedback (see right)

## Ozone radiative feedback




The radiative feedback ($Wm^{-2}$) from ozone changes in a $CO_2$ doubling simulation is dominated by the stratospheric ozone changes in general, and by those in the lowermost tropical stratosphere in particular.
It is, thus, negative in the global mean, decreasing $CO_2$ climate sensitivity.

## Stratospheric water vapour feedback changes




Temperature and water vapour response induced by $CO_2$ doubling in a simulation with interactive chemistry.

Response change from the 2xCO2 simulation without chemistry to the 2xCO2 simulation including chemistry.

The ozone feedback in the lowermost tropical stratosphere induced by $CO_2$ doubling in turn leads to a smaller warming of the tropical cold point temperature than occurring in the respective simulation without interactive chemistry. Consequently, the stratospheric water vapour increase and radiative feedback are reduced, if chemical feedbacks are included.

## Main results

- The climate sensitivity to $CO_2$ is reduced in equilibrium climate change simulations if chemical feedbacks are included in the climate model setup. The damping effect is moderate but significant (3.4%) in a $CO_2$ doubling simulation.
- The main contributor to this effect is a negative feedback from stratospheric ozone, mainly caused by an ozone decrease in the lowermost tropical stratosphere that results from enhanced upwelling of air over the warming tropical ocean.
- Stratospheric water vapour feedback is working as a amplifier of the negative ozone feedback through coupling via interactions at the tropical cold point.
- The climate sensitivity reduction induced by interactive ozone appears to grow with increasing external forcing, reaching 8.4% in a $CO_2$ quadrupling simulation.
- There are indications that the damping effect of chemical feedbacks may even be enhanced by methane feedbacks, yet this conclusion remains indicative due to conceptual limitations in the model setup used for this study (Dietmüller et al., 2014).

**References**

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Muthers, S, et al, The coupled atmosphere–chemistry–ocean model SOCOL-MPIOM, Geosci Model Dev 7: 2157-2179, doi:10.5194/gmd-7-2157-2014 (2014).

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